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ON THE PRIMORDIAL ABUNDANCE OF ^{7}Li *

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The consistency of the standard model of big bang nucleosynthesis[1] has again been positively tested with recent measurements of Be[2-5] and B[6] in population II hot halo dwarf stars. It is evident that the observed Be (and B) is not of primordial origin, as it lacks the plateau (a fixed abundance over a wide range of low metallicities and high temperatures) which is evidenced in the ^{7}Li data[7-11]. These elements are produced in the big bang[12], but at a level that is several orders of magnitude below that of recent abundance measurements. The origin of the observed Be and B, appears to be galactic cosmic ray (GCR) spallation[13-15]. Produced via GCR spallation along with the observed abundance of Be and B, should be significant amounts of accompanying ^{7}Li, which adds to the primordial Li coming from the big bang. It has been shown that the simplest models of GCR spallation can account for the observed Be and B abundances while maintaining consistency (within stated errors) with big bang nucleosynthesis and the ^{7}Li abundance[15]. Here, we would like to go a step further and use the Be (and B) data to extract a derived abundance for primordial ^{7}Li. Then using the derived baseline, one can add to it the predictions of GCR-spallation[14,15] (which is metallicity-dependent) and compare this to the observed ^{7}Li abundances. As anticipated, we find very good agreement between the simplest model and the data. We will also briefly comment on non-standard models as well.

The dominant product of big bang nucleosynthesis[1] is ^{4}He, which is produced with an abundance by mass of Y ~ 0.24 (leaving a primordial Hydrogen mass fraction of ~76%). ^{4}He is accompanied by lesser amounts of D and ^{3}He, (D, ^{3}He)/H ~ 10^{-5} (by number). In contrast, ^{7}Li is produced with even lower abundances (^{7}Li/H) ~ 10^{-10} in the standard model. The fact that the predicted abundances of these light element isotopes can be explained over this range of nearly 10 orders of magnitude, in the simplest nucleosynthesis model is clearly a great success of the model. If one is restricted to the standard model, fixing the number of neutrino flavors $N_\nu = 3$, along with recent measurements of the neutron mean life $\tau_n = 889.1 \pm 2.1$ s leaves only the baryon to photon ratio $\eta \equiv n_B/n_\gamma$ as the sole surviving adjustable parameter. Indeed, consistency of the light element abundances fixes this parameter as well to a very small range around[1] $\eta = 3 \times 10^{-10}$.

Big bang nucleosynthesis calculations can also predict the primordial abundances of other light element isotopes[12], namely ^{6}Li, ^{9}Be, ^{10}B and ^{11}B. These isotopes are produced in significantly smaller quantities (^{6}Li/H) ~ 10^{-14}, (^{9}Be/H) ~ 10^{-18}, (^{10}B/H) ~ 10^{-20}, (^{11}B/H) ~ 10^{-18}, for $\eta = 3 \times 10^{-10}$. Though higher (and lower) abundances of these isotopes can be achieved (at higher/lower values of η) the abundances of the lighter isotopes would then no longer remain consistent with observations.

Since the observation of the ^{7}Li plateau[7], it has been argued that the plateau value of (^{7}Li/H) ~ 10^{-10} corresponds to primordial ^{7}Li. Hence, ^{7}Li has been made a key element in tests of consistency for big bang nucleosynthesis. The stars making up the plateau (there are nearly 40 of them now) are all population II halo dwarfs. They have low metallicity, [Fe/H] $\lesssim$ -1.3 ([X/H] corresponds to the log abundance by number relative to the solar value), with some going as low as [Fe/H] = -3.5. They also have high surface temperatures T > 5500K. Cooler halo stars are observed to have significantly less ^{7}Li, confirming stellar models which depict convective depletion at T $\lesssim$ 5500K (see eg. ref.16). Over the entire range (5500 < T < 6300 and -3.5 $\lesssim$ [Fe/H] $\lesssim$ -1.3) the ^{7}Li abundance is remarkably constant. The plateau stars have a well determined mean

$$[^7\mathrm{Li}] = 2.08 \pm 0.02 \tag{1}$$

(where we use the astronomical convention [^{7}Li] = 12 + [^{7}Li/H]) and show a dispersion of about 0.12 which is consistent with the observational uncertainty in the measurements.

Furthermore, there are no significant departures from constancy in [Li] in these stars. The χ^2, per degree of freedom, dispersion from the mean value is $\chi^2 = 1.26$. There is no correlation with metallicity,

$$[\mathrm{Li}] = 2.11 \pm 0.09 + (0.02 \pm 0.04)\,[\mathrm{Fe/H}] \tag{2}$$
$$\chi^2 = 1.26 \quad r = -0.056$$

and only the faint hint of a correlation with temperature,

$$[\mathrm{Li}] = 0.45 \pm 0.62 + (0.0003 \pm 0.0001)\,T \tag{3}$$
$$\chi^2 = 1.11 \quad r = 0.390$$

corresponding to a positive slope of 3.6×10^{-14} for d(Li/H)/dT, in good agreement with the value given by Hobbs and Thorburn[11]. This lack of trend has led strong credence to the assumption of a primordial origin to population II lithium.

Recently a (growing) number of halo dwarfs have been shown to have a measurable ^{9}Be abundance[2-5], (most of which are in the ^{7}Li data set). Unlike ^{7}Li, the ^{9}Be abundance is strongly correlated to metallicity,

$$[^9\mathrm{Be}] = (-10.19 \pm .54) + (1.13 \pm .27)\,[\mathrm{Fe/H}] \tag{4}$$
$$\chi^2 = 0.28 \quad r = 0.93$$

Thus it is clear that the observed ^{9}Be is not primordial. As the standard model prediction for primordial[12] ^{9}Be/H is ~ 10^{-18}-10^{-17} while the observed abundances are 10^{-13} -10^{-12}, the strong correlation is not really a surprise. Note that unless a ^{9}Be plateau can be established, the measured ^{9}Be abundances per se, say very little about standard or even non-standard nucleosynthesis since no primordial value is determinable. Unlike the case for ^{4}He, where the primordial component is dominant and one can determine a definite primordial value by extrapolation to near zero metallicity, the primordial component of ^{9}Be is presumably negligible compared with the observed ^{9}Be.

For completeness, we note that there are new observations[6] of B in three halo dwarfs. Again there is a strong correlation with metallicity

$$[B] = (-8.48 \pm .67) + (1.42 \pm .33)\,[Fe/H] \tag{5}$$
$$\chi^2 = 0.27 \quad r = 0.99$$

And like Be, the measured abundances are orders of magnitude above the big bang yields.

These new observations are in fact very relevant to our understanding of galactic-cosmic-ray spallation processes[13]: p, α on ^{4}He, C, N and O. By making a simple set of assumptions[14]: a cosmic-ray spectrum, much as we see it today; and C-N-O abundances characteristic of extreme Pop II stars, namely [C/H] ≈ [N/H] ≈ [Fe/H] and [O/Fe] ≈ 0.5, one finds some general results of GCR spallation[14,15]. The abundances of [Be] and [B] are linearly correlated with [Fe]; [^{7}Li] is less strongly correlated as much of the ^{7}Li is produced by $\alpha + \alpha$ collisions rather than by spallation on CNO; ^{6}Li/^{7}Li ≈ 0.9 and B/Be ~ 12 - 14.5. Note the large ^{6}Li/^{7}Li ratio. As ^{6}Li is depleted in significantly larger quantities than ^{7}Li and Be, observation of ^{6}Li in halo dwarfs is expected to be more difficult[16,17]. The GCR-spallation does predict a possibly measurable amount of ^{6}Li in the very hottest halo dwarfs, ($T \gtrsim 6200$ K) when Li is not depleted by mass-loss or diffusion[18].

Recently the consistency of big bang nucleosynthesis has been examined regarding the Be and Li abundances[15]. It was shown that although a sizeable fraction of the total ^{7}Li may be produced, the observed ^{7}Li is consistent with the prediction of GCR-spallation and a primordial value of [Li] = 2.00 - 2.12. This consistency can be shown on a star-by-star basis for the twelve stars with observed ^{7}Li and ^{9}Be, with the possible exception of one star HD76932, which is consistent at the 2-σ level (note that HD76932 is generally not regarded to be a plateau star because of its high metallicity). Furthermore the newly measured B abundances are consistent (within observational uncertainties) to the GCR-spallation predictions.

One can go further than the consistency check of Walker et al.[15] by systematically subtracting out the GCR-spallation produced ^{7}Li from the observations. Of the twelve stars with observed ^{9}Be, ten have measured ^{7}Li. Of these ten we omit HD76932 since as mentioned above, it is usually omitted from the ^{7}Li plateau data set and HD34328 which is reported[5] to be a dubious measurement (due to an uncertain spectrographic setting). This leaves us with eight stars with which we attempt to extract the primordial ^{7}Li abundance. These stars are listed in Table 1 along with

[Fe/H] (an unweighted mean of measured values) the GCR-spallation ratio $^7Li/^9Be$, the observed ^9Be and ^7Li abundances and the derived primordial abundances from

$$(^7Li/H)_{BB} = (^7Li/H)_{obs} - (^7Li/^9Be)_{GCR}\,(^9Be/H)_{obs} \qquad (6)$$

When available we use the weighted average of observed C, N and O in these stars, otherwise we use the simple anzatz given above for Pop II stars. Observational errors in all measurable quantities have been propagated lending to the somewhat larger errors for $[^7Li]_{BB}$ shown in the Table. The weighted mean for these eight stars is

$$[Li]_{BB} = 2.01 \pm 0.07 \qquad (7)$$

Note that because of the greater uncertainty, the 2σ upper limit is essentially the same as one would obtain from Eq. (1). The dispersion in observed ^7Li of these eight stars is given by a χ^2 per degree of freedom of 1.73 though because of the larger uncertainties the χ^2 per degree of freedom of $[Li]_{BB}$ is small, 0.26.

In principle one can repeat this exercise with the B data shown in Table 2. The implied primordial abundance of ^7Li from the B data (by an analogous procedure) is also [Li] = 2.01 ± 0.06, in perfect (coincidental) agreement with the value derived from Be. We are also encouraged that the B/Be ratios are consistent with the GCR-predictions[15].

Given a primordial value of [Li] = 2.01, we can now determine the ^7Li abundance as a function of [Fe/H], using [C/H] = [N/H] = [Fe/H] and [O/Fe] = 0.5 so that[15]

$$[Li]_{GCR} = 1.59 + \log\,(1+4.53 \times 10^{[Fe/H]}) \qquad (8)$$

and

$$(\mathrm{Li/H})_{\mathrm{total}} = (\mathrm{Li/H})_{\mathrm{BB}} + (\mathrm{Li/H})_{\mathrm{GCR}} \tag{9}$$

(Note the normalization has been fixed by $(^9\mathrm{Be/H})_{\mathrm{OBS}} = (^9\mathrm{Be})_{\mathrm{GCR}}$ which fixed the exposure time Δt = 10.7 Gyr. [Li] total is plotted as a function of [Fe/H] in the Figure along with the baseline $[\mathrm{Li}]_{\mathrm{BB}}$ = 2.01 (dashed) the ^{7}Li data set and the mean of the data [Li] = 2.08 (dotted). Given the uncertainties in the measurements and calculations, one cannot identify a discrepancy between the data and the model prediction (solid curve). The χ^2 - per degree of freedom now is 1.75 (Note that could be even lower if we make the correction suggested by Hobbs and Thorburn[11]) on the left-most discrepant star G238-30. They use a higher surface temperature leading to [Li] = 2.05 rather than [Li] = 1.84 for the same equivalent width. This correction would reduce χ^2 to 1.52. We are not aware of any corrections suggested for the other two somewhat discrepant stars. One should note that we have neglected the effects of diffusion (a point we will return to shortly). The models of Deliyannis et al.[16]) using standard Li isochrones is best fit with an initial abundance of [Li] = 2.17 very close to the model prediction of [Li] ≈ 2.15.

Finally, we would like to discuss briefly the implication of these results to non-standard models; inhomogeneous nucleosynthesis[19,20]) and extreme depletion in rotational models[21]). It is sometimes remarked[3]) that the "high" Be abundances combined with a possible discrepancy between primordial and GCR-nucleosynthesis (which we argue here is not present) may be a signature for inhomogeneous nucleosynthesis. However, until a plateau can be established for ^{9}Be, there is no signature, standard or not, for any primordial production ^{9}Be. Furthermore, as it was shown[20]) that the inhomogeneous models, are incapable of significantly altering the conclusions of standard nucleosynthesis when all $A \leq 7$ light element isotope abudance constraints are used, it seems unlikely that ^{9}Be will be an exception. Preliminary calculations bear this out[12,22]). In other words, accurate inhomogeneous nucleosynthesis calculations also do not appear to yield Be/H as high as observed in the Pop II stars.

Next we come to the stellar models of Pinsonneault et al.[21]) (PDD) with rotation and a reported depletion of primordial ^{7}Li by an order of magnitude. These models consider the possible effects of diffusion effects beyond standard stellar models arising from including large rotationally induced mixing. PDD take a limited high range for stellar angular velocities ranging from 1/20 to 1/2 of the critical break-up value, choose high rotationally induced mixing rates, and find with these assumptions that a primordial value [Li] = 3.1, can be depleted down to a plateau with relatively small dispersion. They claim consistency with the data. With such a high value for the primordial abundance, the GCR-produced ^{7}Li would be insignificant. (Recall that in the absence of depletion, GCR spalltion requires an effective exposure time of about 10 Gyr, thus even though Be suffers much less depletion than Li[23]) the time scale for producing Be by GCR-spallation would have to correspondingly increased, perhaps by an untenable factor as large as 3.) However, PDD find that their model predicts a dispersion of 0.3dex for stellar age as large as 20 Gyr. For smaller ages such as 13 Gyr, the models predict a dispersion of .5dex. Recall that the data shows only a dispersion (accountable by the observational uncertainties) of 0.12dex. The chance of this occurring is quite (extremely) remote for the 20 (13) Gyr models. Clearly, a larger range in angular velocities will produce even more dispersion. An important additional failure for these depletion models is that they distinctly predict that the dispersion should be largest at *high* temperatures, the data clearly contradict this by showing the opposite trend.

Finally we note that the current Pop I stellar abundances of [Li] ~ 3 are easily understood relative to the primordial abundances of [Li] ~ 2 by the addition of ^{7}Li from AGB stars (as well as ~10% addition of GCR-spallation produced ^{7}Li that accompanies the production of the observed ^{6}Li). Smith and Lambert[24]) have observed significant enrichments of Li in certain AGB stars. It has been shown[25]) that reasonable estimates of the frequency of such stars and their subsequent mass-loss would naturally result in Li enhancements in the Galaxy that agree with the observed Pop I abundance. The production of the AGB Li is presumably via the Cameron-Fowler[26]) process ^{3}He(α,γ)^{7}Be(beta-decay)^{7}Li in the outer convective zone. Thus not only is a high initial Li not needed but could even cause excesses since the observed AGB Li would have to be added and little subsequent destruction would be allowed without also destroying the ^{6}Li which is only known to be able to be produced via GCR-spallation.

While it may be possible to eventually add enough parameters to the theory to match the data, at present we find no justification for a departure from the standard model which so well explains the observational data in the simplest possible way.

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Table 1

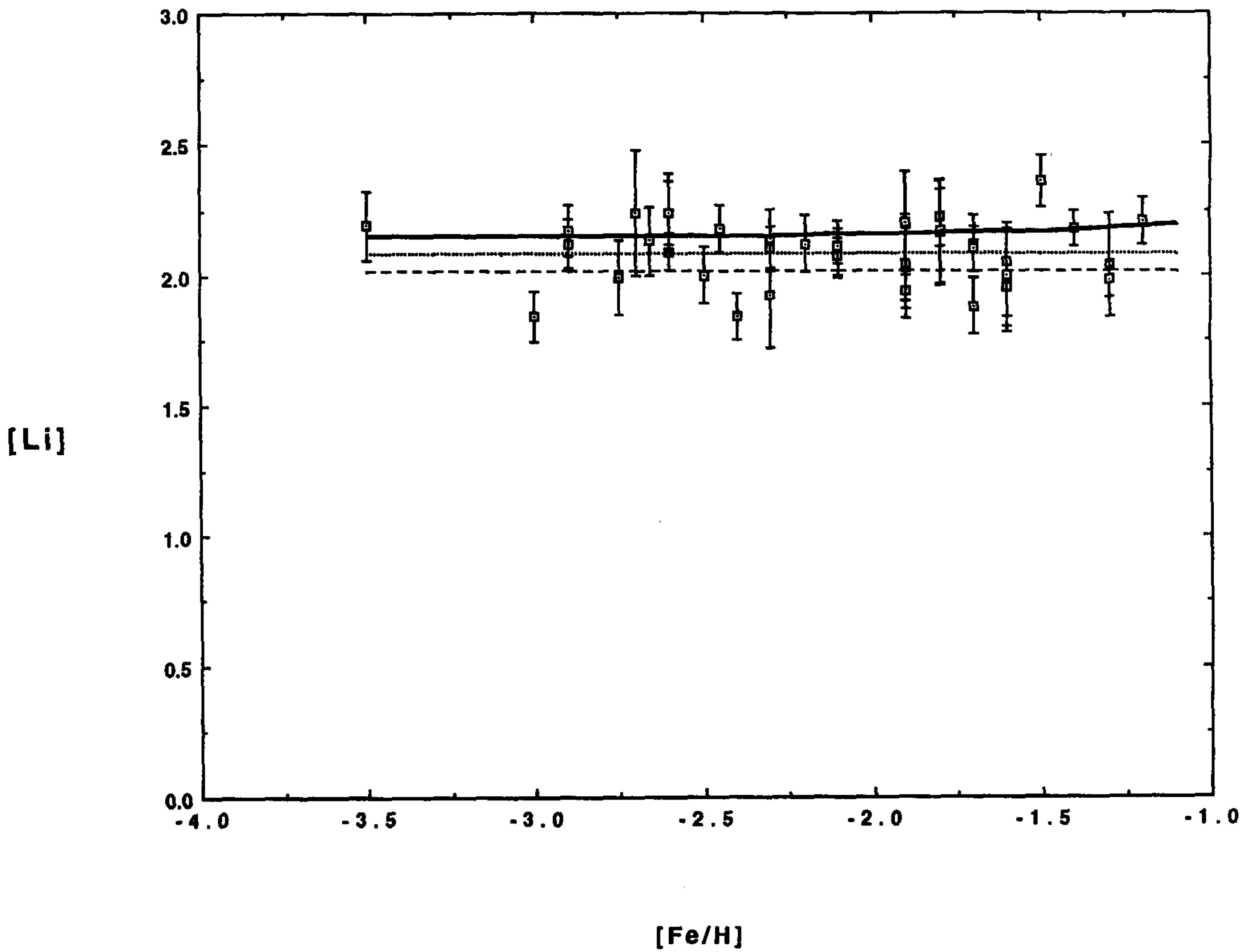
Star	[Fe/H]	$(^7Li/Be)_{GCR}$	$[Be]_{obs}$	$[Li]_{obs}$	$[Li]_{BB}$
HD 16031	-1.9	80±30	-0.37±.25	2.03±.20	1.86±.32
HD 134169	-1.2	11±2	+0.65±.4	2.21±.09	2.06±.22
HD 140283	-2.6	234±14	-1.04±.19	2.09±.07	2.01±.09
HD 160617	-1.9	38±9	-0.47±.18	2.20±.20	2.16±.22
HD 189558	-1.3	26±8	+0.00±.4	2.04±.20	1.92±.30
HD 201891	-1.3	12±4	+0.40±.4	1.98±.07	1.82±.22
HD 213617	-2.2	161±61	-0.65±.25	2.17	2.05±.28
BD 23° 3912	-1.5	43±16	+0.30±.4	2.36±.10	2.16±.30

Table 2

Star	[Fe/H]	$(^7Li/B)GCR$	$[B]_{obs}$	$[Li]_{obs}$	$[Li]_{BB}$
HD 19445	-2.1	7±2	0.4±.2	2.07±.07	2.00±.09
HD 140283	-2.6	17±1	-0.1±.2	2.09±.07	2.04±.08
HD 201891	-1.3	0.9±0.25	1.7±.4	1.98±.07	1.70±0.40

Figure Caption

Figure 1: The ^7Li data as a function of the [Fe/H]. The dotted line corresponds to the mean of the data [Li] = 2.08, $\chi^2 = 1.26$. The dashed line corresponds to the extracted primordial value of [Li] = 2.01. The solid curve corresponds to the sum of the primordial value and the metallicity dependent GCR-spallation produced ^7Li with $\chi^2 = 1.75$.


[Li]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-4.0
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
[Fe/H]